to shed light on poorly understood piercement structures that seem to be relatively common in deep sedimentary basins.

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Repeat Hydrography Cruises Reveal Chemical Changes in the North Atlantic

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The U.S. contribution to a large international effort to document long-term trends in carbon storage and transport in the global oceans by reoccupying selected hydrographic sections on decadal timescales began with three North Atlantic cruises in 2003. The initial results from these reoccupation cruises have shown significant long-term changes in oxygen, carbon dioxide (CO_2), and several other measurable parameters since the last global survey, which occurred in 1993.

The ocean has a memory of the climate system and is second only to the Sun in affecting variability in the seasons and long-term climate change. The ocean stores an estimated 1000 times more heat than the atmosphere, and 50 times more carbon. Additionally, the key to possible abrupt climate change may lie in deep-ocean circulation.

Accordingly, the U.S. Climate Variability and Predictability (CLIVAR)/CO_2 Repeat Hydrography component of the Global Earth Observing System of Systems (GEOSS) sustained ocean observing system for climate consists of a systematic reoccupation of select hydrographic sections in order to quantify decadal changes in the storage and transport of heat, freshwater, and CO_2. The CLIVAR/CO_2 Repeat Hydrography program builds upon earlier programs (e.g., the World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Survey (JGOFS) during the 1990s) that have shown where atmospheric constituents are stored in the oceans and have provided full water column data sets against which future changes can be measured. [*Sabine et al.*, 2004a].

This program should provide significant information about how changing biochemical processes may affect carbon distributions and sinks on decadal timescales. The program is also designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or human-induced activity. For instance, global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can be followed through long-term measurements.

In addition, the program will provide reference data for the sensor calibration (e.g., www.argo.ucsd.edu) and support for continuing model development that could lead to improved forecasting skill for oceans and global climate.

Historical Background

Studies over the last two decades have increased the understanding of many aspects of the carbon cycle in the oceans. However, it is still uncertain how to interpret the sum of these studies for all of the oceans. For example, *Bates et al.* [2002] suggested that a lack of strong wintertime mixing in the subtropical mode waters of the North Atlantic Ocean during the positive phase of the North Atlantic Oscillation (NAO) may help to explain why subsurface dissolved inorganic carbon (DIC) concentrations increased almost twice as fast in the early 1990s as surface concentrations near Bermuda.

Moreover, *Gruber et al.* [2002] conducted modeling studies that indicated that the NAO could account for an interannual variability of about ±0.3 petagram carbon (Pg C) yr^{1} in the North Atlantic carbon sink. Similarly, *Emerson et al.* [2001] and *Ono et al.* [2001] reported on increases in apparent oxygen utilization (AOU) in the upper thermocline of the eastern and western North Pacific Ocean, respectively, which they attributed to recent decadal changes in circulation.

The following year, *Keller et al.* [2002] examined a larger area of the Pacific and also found AOU changes. However, they suggested that compensating changes in the opposite direction may be found deeper in the water column.

These studies examined different regions, depth zones, and time periods using differing approaches, making it difficult to assess if the

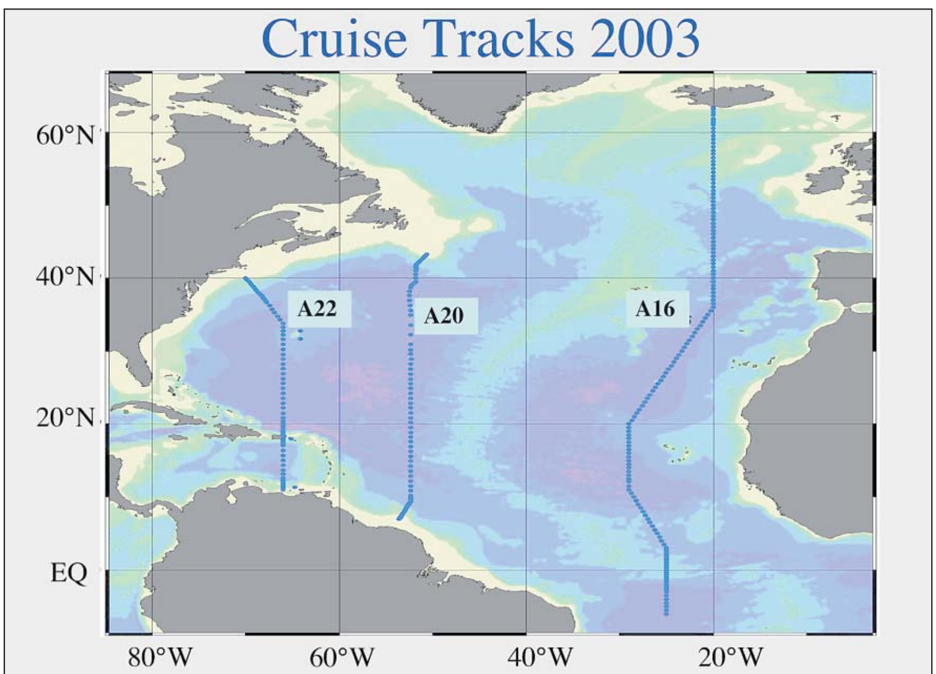

Fig. 1. Map of CLIVAR/CO_2 Repeat Hydrography Program hydrographic sections in the North Atlantic during 2003. The U.S. A16N (along 20°W), A20 (along 52°W), and A22 (along 66°W) cruises are designated with solid blue dots.

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signals were coherent across an entire basin. Although the list of local and regional variations of physical and chemical parameters is growing quickly, comprehensive basin-wide water column studies of decadal changes are needed to develop a global-scale appreciation of the changes and to assess the large-scale feedbacks between the ocean carbon cycle and climate.

Recent Results in the North Atlantic

The U.S. CLIVAR/CO_2 Repeat Hydrography Program started in 2003 with the reoccupation of three WOCE sections in the North Atlantic: A16N, A20, and A22 (Figure 1). This program is the U.S. contribution to the global biogeochemical and hydrographic resurvey under the auspices of the CLIVAR program.

A16N is a meridional section nominally along 20°W in the eastern basin of the North Atlantic that was last occupied by U.S. investigators in 1993. The U.S. National Oceanic and Atmospheric Administration ship *Ronald H. Brown* departed from Iceland in June 2003 conducting full water column measurements to 6°S.

The other two sections were conducted on the U.S. R/V *Knorr* from Woods Hole, Massachusetts, between September and November of 2003. The first leg (A20) was along 52°W and ended in Trinidad; the second leg (A22) was along 66°W and ended back in Woods Hole (Figure 1).

During all of these sections, samples were analyzed onboard for DIC, salinity, dissolved oxygen, nutrients, titration alkalinity, and chlorofluorocarbons. Water samples were collected for shore-based analyses of helium, tritium, dissolved organic carbon (DOC), Carbon-13, Carbon-14, and trace metals.

The analysis of the A16N cruise data shows that between the 2003 section and earlier occupations in 1988, 1993, and 1998, significant long-term changes in water mass properties have occurred. These changes include increases in temperature, salinity, and DIC and decreases in dissolved oxygen observed just below the subpolar mode water (north of 35°N below 500 m).

The increase in AOU, ranging from 5 to 50 micromoles per kilogram (μmol kg^{-1}) observed in the subpolar region of the North Atlantic (Figure 2), appears to be due to changes in the regional circulation and ventilation processes in the region during the decade prior to the 2003 occupation compared with the years prior to the earlier samplings [*Johnson et al.*, 2005]. Changes in biological production, organic matter export, and remineralization rates may also play a role. Regions in the water column with large increases in AOU tended to have increases in pCFC ages, indicating that the AOU changes may be driven by circulation or ventilation changes after the 1995–1996 NAO negative shift.

The data also indicate significant increases of DIC in the uppermost surface waters (0–500 m) and near the base of the subpolar mode water (Figure 3). The surface water increases (530 μmol kg^{-1}) are due primarily to the uptake of anthropogenic CO_2 from the atmosphere. The deepwater increases of about 10–20 μmol kg^{-1} found just below the subpolar mode water at about 600–1000 m are highly correlated with the AOU increases, indicating that these DIC increases are most likely due to changes in regional circulation, remineralization, and ventilation. In contrast, the DIC at depths >1500 m showed very little change [*Wanninkhof et al.*, 2004].

During the A22/A20 cruises in the western North Atlantic, similar changes in DIC and AOU were also observed between 0 and 1200 m. The increases of DIC in the subtropical mode water (STMW) there are greater than expected from invasion of anthropogenic CO_2 from the atmosphere. The increases may also be the result of decadal changes in the local circulation and ventilation processes in the North Atlantic, and/or changes in new production and remineralization of organic matter along the flow path. Preliminary estimates indicate a mean CO_2 uptake rate of approximately 0.7± 0.2 mol m^{-2} yr^{-1} for the North Atlantic during the past decade, somewhat lower than what has been observed in the North Pacific [*Peng et al.*, 2003; *Sabine et al.*, 2004b]. This preliminary result was unexpected because *Sabine et al.* [2004a] have shown that over the course of the industrial era, the North Atlantic has taken up more than three times the amount of anthropogenic CO_2 per unit area than the North Pacific. This surprising result may be related to the 1995–1996 phase shift from high NAO to lower NAO.

As U.S. and international investigators collaborate on combining and analyzing data sets, the spatial variability of the carbon and oxygen distributions in the Atlantic Ocean and how they are affected by decadal changes in circulation and ventilation processes should be able to be better determined.

These cruises also provided the first ever high-resolution basin-scale sections of DOC and dissolved iron (Fe) in the North Atlantic.

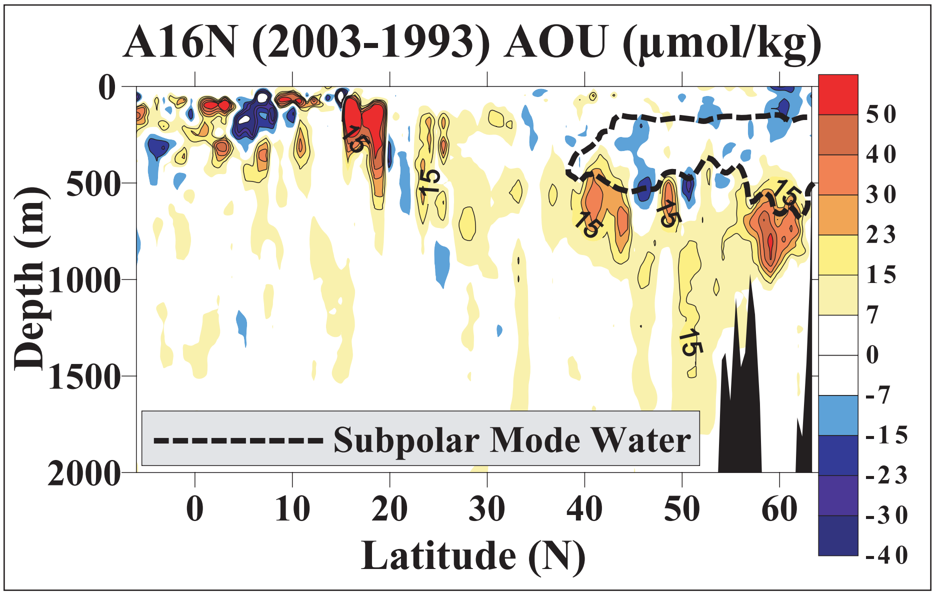

Fig. 2. Difference of apparent oxygen utilization between 2003 and 1993 as a function of latitude and depth along the A16N track in the North Atlantic.

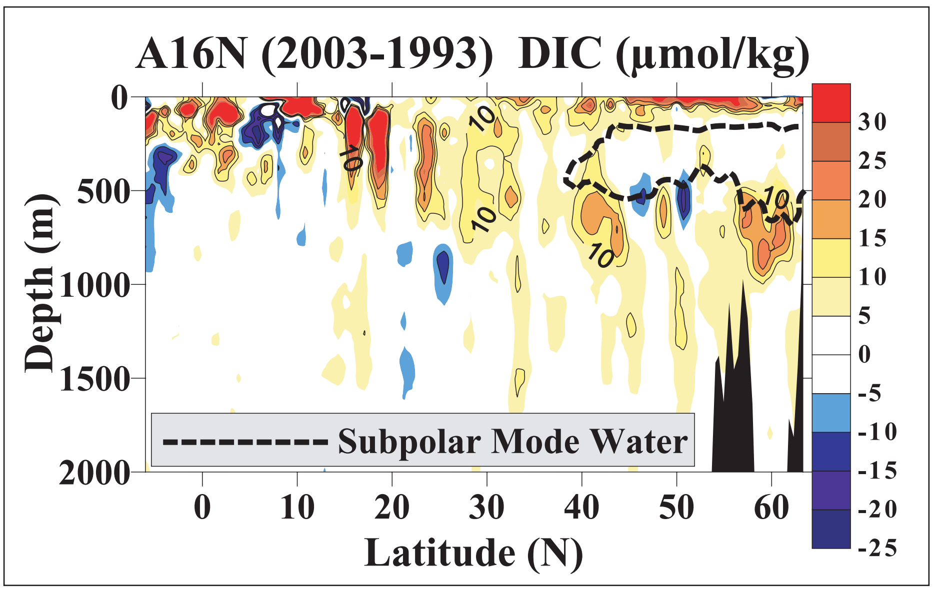

Fig. 3. Difference of the dissolved inorganic carbon (in µmol/kg) between 2003 and 1993 as a function of latitude and depth along the A16N cruise track in the North Atlantic.

The new data revealed information on the export of DOC with the formation of North Atlantic Deep Water. In waters deeper than 2000 m, DOC concentrations ranged from 48 μM in waters characteristic of North Atlantic Deep Water to as low as 39 μM in waters characteristic of Antarctic Bottom Water [*Goldberg et al.*, 2004].

The dissolved Fe data showed enrichments in the water masses directly underneath the Saharan dust input region west of Africa, which apparently are the result of soluble aerosol Fe loading, biological uptake, and intense Fe regeneration [*Landing et al.,* 2004]. These highly resolved data sets are already changing the understanding of carbon cycle processes in the Atlantic, and they will be used to assess temporal as well as spatial trends of these important parameters.

The U.S. CLIVAR/CO_2 Repeat Hydrography Program is jointly sponsored by the U.S. National Science Foundation's Physical and Chemical Oceanography programs and NOAA's Office of Climate Observation, with contributions from NASA and the U.S. Department of Energy. The program currently seeks junior level scientists (postdocs and assistant level scientists) for participation as co-chief scientists, and graduate students for general participation during upcoming cruises to the Pacific and Indian oceans.

For more information, visit the CLIVAR/CO_2 Repeat Hydrography Program Web site at http://ushydro.ucsd.edu/index.html.

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NEWS

Katrina and Rita Were Lit Up with Lightning

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Hurricanes generally produce very little lightning activity compared to other noncyclonic storms, and lightning is especially sparse in the eye wall and inner regions within tens of kilometers surrounding the eye [*Molinari et al.*, 1994, 1999]. (The eye wall is the wall of clouds that encircles the eye of the hurricane.) Lightning can sometimes be detected in the outer, spiral rainbands, but the lightning occurrence rate varies significantly from hurricane to hurricane as well as within an individual hurricane's lifetime.

Hurricanes Katrina and Rita hit the U.S. Gulf coasts of Louisiana, Mississippi, and Texas, and their distinctions were not just limited to their tremendous intensity and damage caused. They also differed from typical hurricanes in their lightning production rate.

Observations by the Los Alamos National Laboratory's Sferic Array (LASA) [*Shao et al.*, 2005] lightning system show that a significant amount of lightning activity occurred within both storms. Lightning rates were as high as 600 flashes per hour during Katrina, and lightning was detected along the eye wall during the transition stage from lower to higher hurricane classification categories in both hurricanes. During the intensification of these hurricanes, there was sufficient convection in the eye wall to produce multiple lightning events.

This report presents LASA's initial lightning observations. A more thorough scientific study is currently under way.

LASA detects "very low" and "low" radio frequency (VLF/LF) signals produced by lightning and uses time-of-arrival techniques to locate the lightning sources. LASA began operating in April 2004, and the array can locate even weak lightning signals several hundreds of kilometers away.

Six stations in the U.S. Great Plains and two stations in Florida participated in the Katrina and Rita observations, providing kilometer-scale accuracy for the source locations in the Gulf region.

Two snapshots of lightning activity during Katrina are shown in Figure 1. Each snapshot contains two hours of lightning events geolocated by LASA. The center of the hurricane is marked by the blue disk, and the size of the disk represents the approximate diameter of the eye wall as reported by the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center. The top panel shows lightning activity from 1730:00 to 1930:00 UTC on 28 August 2005. At that time, Katrina was in its first half of the Category 5 stage.

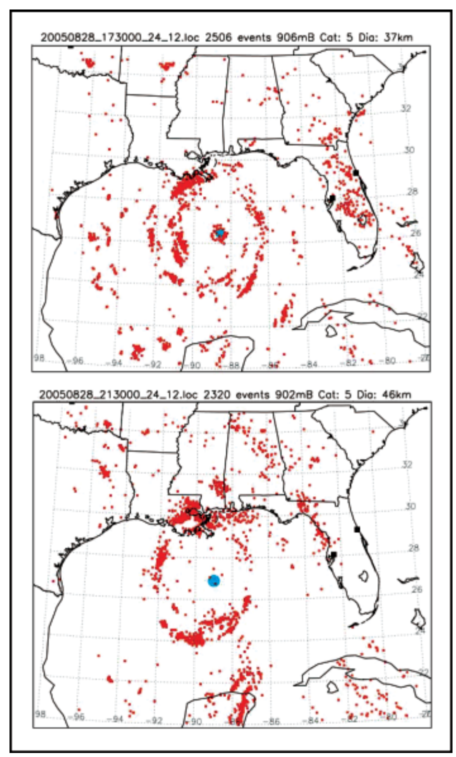

Fig 1. Lightning observations of Hurricane Katrina. (top) Geolocated lightning events (red dots) during 1730:00–1930:00 UTC, 28 August 2005. (bottom) Lightning events during 2130:00–2330:00 on the same day. Blue discs show the position and size of the hurricane eye.

A total of 52 lightning events were detected encircling the eye wall during that time, indicating strong vertical convection in the eye